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This paper describes the methods employed to apply probabilistic modeling techniques to the International Space Station (ISS) power system. These techniques were used to quantify the probabilistic variation in the power output, also called the response variable, due to variations (uncertainties) associated with knowledge of the influencing factors called the random variables. These uncertainties can be due to unknown environmental conditions, variation in the performance of electrical power system components or sensor tolerances. Uncertainties in these variables, cause corresponding variations in the power output, but the magnitude of that effect varies with the ISS operating conditions, e.g. whether or not the solar panels are actively tracking the sun. Therefore, it is important to quantify the influence of these uncertainties on the power output for optimizing the power available for experiments.

I. Introduction

Electric power system (EPS) performance models are critical to spacecraft such as the International Space Station (ISS), to assure that sufficient power is available to support core system and payload power needs. To date, such EPS models have always been deterministic, due to lack of availability of probabilistic methods/tools. However, in recent years, probabilistic modeling techniques have been developed and applied successfully for structural problems. These techniques allow the model to account for the uncertainties in the model random (input) variables, and produce results that include the variation in response variables caused by these uncertainties. This effort attempted to apply these probabilistic techniques to the area of EPS performance modeling, using the ISS power system as the demonstration case.

Power is supplied to the space station by solar panels. These panels generate power only when they are exposed to the sun. Some of the generated power is stored in batteries during this time. When the solar panels are not exposed to the sun, including an eclipse, the power stored in the batteries is used. Figure 1 shows a representation of the architecture of the EPS. Note that the EPS includes DDCUs (dc-to-dc Converter Units), which convert the power from the primary distribution voltage to a regulated voltage used by the various ISS loads. Several such units work in parallel to convert the power. The BCDU (battery charge/discharge unit) controls the charging of the batteries during the sunlight period, and the discharging of the batteries during the eclipse period.

The ISS power system consists of several independent power channels, each of which is a complete power system in itself with a solar array, batteries, and power management and distribution hardware. When complete, there will be eight power channels in the EPS. At the time of the writing of this paper, there are 2 channels on-orbit. The channels are designated by the names 2B and 4B.

The ISS power system is assembled in stages, in-orbit, and when complete, will be the largest power system ever flown in space. Because it is so large, the entire EPS can never be assembled and tested on the ground.

Therefore, all critical system performance assessments are conducted by analysis. To perform these types of analyses, NASA Glenn has developed a computer model of the EPS that is called SPACE¹ (System Performance Analysis for Capability Evaluation). SPACE is a very detailed model of the ISS power system that is able to accurately predict the amount of power that the EPS can produce under any specified operating system. SPACE has been thoroughly validated against telemetry data from the orbiting space station².

SPACE, like nearly every spacecraft power system model is a deterministic model. This means that the result of a SPACE analysis is a single-valued function, which does not account for any uncertainties in the model's input data. To account for its deterministic nature, input data are carefully selected to be conservative, thus giving

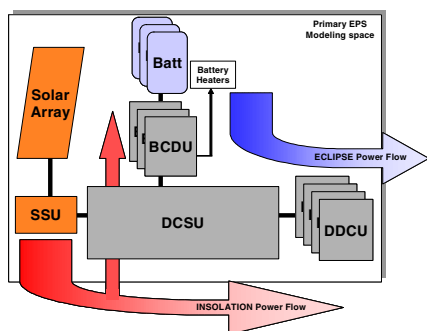


Figure 1 ISS EPS Flow Diagram

confidence that the model will not over predict power capability. However, it would still be very useful to be able to quantify the uncertainty at the system level, as a function of the individual uncertainties in the various model inputs. Such *probabilistic* assessments have proven challenging to perform in the past, as the complex and non-linear interactions between the model inputs require some sort of Monte Carlo-type simulation to capture them. Because SPACE is a large and complex code, running the thousands of cases required by a Monte Carlo method proved computationally expensive to perform.

The value of being able to perform probabilistic assessments is compelling, however, as the results would give ISS designers and operators a much better feel for the power margins that exist when performing a particular operation on the spacecraft. This paper documents the first effort to apply newer probabilistic techniques to spacecraft power system modeling. These techniques were developed in the structural analysis realm, and are being applied to SPACE as a proof-of-concept that they are applicable to the power system analysis world. Applying these techniques to the ISS power system to quantify the probability of minimum available power and the confidence bounds on the power capability may allow the ISS operators to operate the power system closer to its operating limits with higher confidence.

II. Approach and Tools Used

Many different probabilistic approaches and tools have been developed in the recent years and have been applied to determine variations in responses due to inherent variations in the input variables. Application of probabilistic methods have been gaining more and more momentum in practically all engineering disciplines lately, particularly so in aerospace structures^{3,4}. Many publications have been written by personnel at NASA Glenn Research Center on the applications of probabilistic methods. The approach that has been used for this analysis is the perturbation method. This method includes identifying the input variables of the component/system to be analyzed and the response variable(s) of interest. The input variables are perturbed to simulate the inherent uncertainties in them and the corresponding response is calculated using either a software tool or an experiment depending upon the problem at hand. Typically, the influence of these uncertainties on the response variable is quantified using a Monte Carlo technique. Finally, response surface models are developed to predict the variation in the response variables for any variations in the input variables.

The computer software tool FPI (Fast Probability Integrator), a component of NESTEM⁵ was used to run an approximation (but a fairly accurate one) of a Monte Carlo technique. SPACE was used to calculate the power capability. SPACE need only be run a few times, once using all the nominal (or mean) values of the input variables, and then twice more for each variable – perturbing each variable by +1 or -1 standard deviation from the mean. If there are n input variables, there will be $2n+1$ input sets for SPACE analysis. The power capability results for each run were retrieved from the SPACE output and input into FPI along with the corresponding values of $2n+1$ sets of perturbed input variables. These sets of input variables contain a set with all mean values of input variables and additional sets of the same variables with one variable perturbed either positive or negative in each set. FPI also needs information such as standard deviation and distribution type for the input variables. FPI then performs the probabilistic and sensitivity analysis and returns, among other things, the cumulative distribution function (CDF) of the power output and sensitivity coefficients for the input variables. Probability Density Functions (PDF) are created using the CDF results.

At the time of this analysis, SPACE was not configured to automatically run cases while perturbing the input variables, so each case was analyzed separately and results were retrieved by hand. Since this analysis was finished, SPACE has been modified to automatically increment the random variables and perform probabilistic and sensitivity analysis using FPI program without manual interruptions.

III. Variables Influencing the Power Output

There are numerous parameters that can affect the performance of a power system like that of the ISS. These include environmental conditions such as solar flux, component performance parameters such as the efficiency of a power converter, and operational parameters such as the flight mode and orientation of the spacecraft. The values of these parameters cannot be known with complete accuracy for various reasons. For example, the efficiency of a component can be measured in a test on the ground, but that efficiency is only known within the accuracy of the measurement equipment. Also, some environmental parameters can never be known precisely a priori, as they change with time in unpredictable ways. An example of this type of environmental parameter is the Earth albedo, which is the percentage of sunlight that is reflected off of the Earth back into space. It would be very useful to have tools and techniques that could account for all of these uncertainties and their effect on the power produced by the spacecraft.

The intent of this project was to prove that the techniques that were developed for the analysis of aerospace structures can be applied equally as well to the analysis of spacecraft power system. Although, hundreds of different parameters may affect the power output, it was decided to select only 5 different parameters to assess in this prototype study. The five parameters, which cover each of the three types of parameters mentioned above (environmental, component performance, and operational), are:

A. Earth Albedo

Earth albedo is the fraction of sunlight that is reflected off of the surface of the Earth. Since some of that reflected light impinges on the ISS solar arrays, albedo affects both the array's power output and temperature. This factor varies somewhat unpredictably, both throughout the year, and throughout a single orbit. Maximum, minimum and typical values are available based on historical satellite measurements, with the typical value the one that is normally used for most assessments. The typical, or mean, value of this factor is 0.27 for the ISS orbital conditions, and the variation about the mean (which is assumed to be the standard deviation) is 0.09. This standard deviation is assumed with a normal distribution.

B. Attitude Error

This parameter represents an error in the knowledge of the station attitude, in degrees. The ISS attitude is controlled in all three axes (yaw, pitch and roll) to a nominal torque equilibrium attitude, or TEA. However, the station normally experiences slight oscillations about that TEA due to perturbances and controller interactions. These oscillations, although normally very small, can affect the ability of the solar arrays to point at the sun, and thus may affect power production. Although these oscillations can be predicted using attitude dynamics tools, that is often not convenient to do, so it would be useful to assess their impact probabilistically. For this prototype assessment, the attitude knowledge error is assumed to be 3 degrees in each axis and with a normal distribution.

C. DDCU Efficiency

There are several of these 6.25 kW converters on the station, which convert the primary voltage of 160 V (nominal) to the secondary voltage of 124.5 (regulated). The efficiency losses in these boxes are a significant portion of the losses in the power system. This efficiency curve in Figure 2 was determined via a regression fit of many samples from on-orbit telemetry. SPACE uses this curve as an input in order to determine the losses in the power distribution system.

The DDCU efficiency varies with output power (low efficiency at low power, high at high power), so there is no single value to vary for the FPI analysis. Therefore, a new method needed to be developed to handle this type of multi-valued parameter in FPI. It was decided that it would be best to be able to vary the entire curve for each

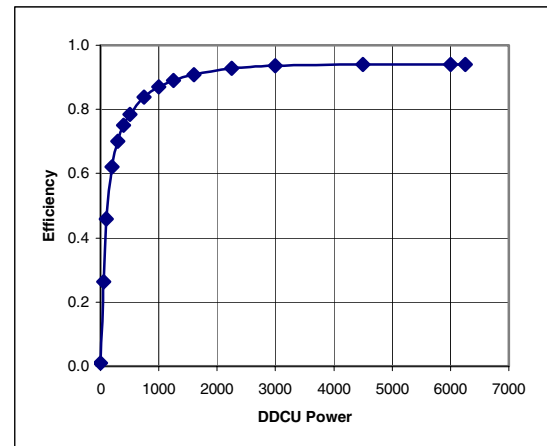


Figure 2 DDCU Efficiency (Input Variable)

run of SPACE in order to simulate both low and high efficiency curves. Therefore, an intermediate variable was introduced, such that a zero value would correspond to the base (or mean) efficiency curve, while ± 1 would correspond to a curve one standard deviation higher or lower than the mean. Average standard deviation of the curve was calculated from the regression fit of the on-orbit data, and that value was determined to be 0.0075. Thus, to produce a perturbed curve for the FPI analysis, the standard deviation is *added or subtracted* to each point in the efficiency curve. A normal distribution is assumed.

D. BCDU Efficiency

The BCDU is the battery charge/discharge unit. It is a device that controls the power flowing into/out of the batteries. Therefore, it has two different efficiency curves, one for charge and the other for discharge. The BCDU discharge efficiency and charge efficiency curves are given in Figure 3 and 4, respectively. The SPACE program uses both curves as inputs to its power availability calculation.

The BCDU efficiency varies with output power for both the charge and discharge processes in a similar manner as the DDCU. Again, since no single value can be used to quantify BCDU power as an input to the FPI code, an intermediate variable is introduced with zero corresponding to the mean curve. The standard deviation of 0.009 is used with normal distribution for perturbing this variable.

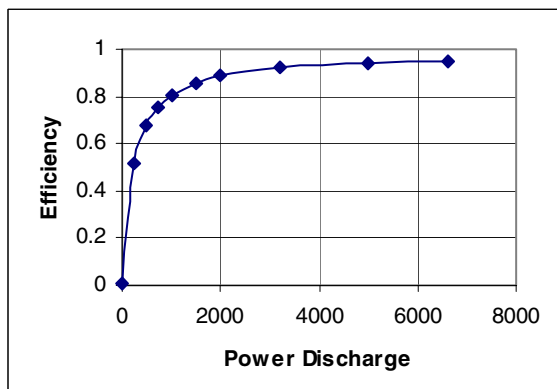


Figure 3 BCDU Discharge Power vs. Efficiency

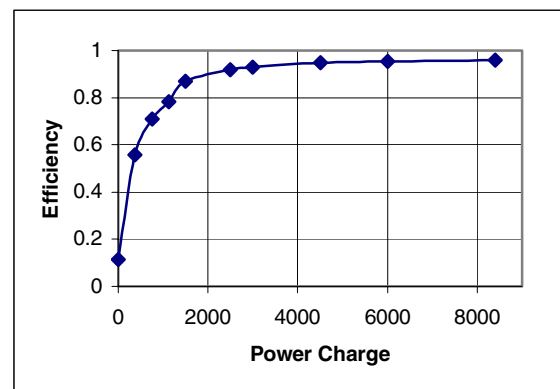


Figure 4 BCDU Charge - Power vs. Efficiency

E. Battery Capacity

This is the capacity of the station's batteries, measured in Ampere-hours (Ahr). The capacity of the batteries changes with time, and is not easily measurable on-orbit. For this example, a distribution was selected that would allow for the capacity to vary between 80 and 100 Ahr. Using a weibull distribution, a mean value of 95.5 Ahr, and a standard deviation = 8.62 Ahr produced the desired distribution, as shown in Figure 5.

The mean values and standard deviations of all the five variables with the type of probability distributions are summarized in Table 1. The baseline and reduced standard deviations shown in this table are used in the analyses cases as described latter in the report.

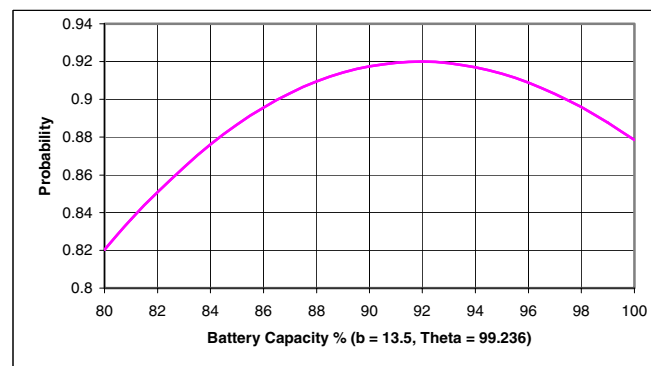


Figure 5 Battery Capacity – Truncated Weibull Distribution

Table 1: Mean Values, Standard Deviations and Type of Distribution of Five Variables

Random Variable	Mean Value of Variables	Baseline Standard Deviation	Reduced Standard Deviation	Type of Distribution
Earth Albedo	0.27	± 0.09	± 0.045	Normal
Attitude Error	-10.0	± 3.0	± 1.5	Normal
Battery Capacity	95.5	± 8.62	± 4.31	Weibull
BCDU Efficiency Charge/Discharge	Shown in Figure 4	± 0.009	± 0.0045	Normal
	Values in Figure 3	± 0.009	± 0.0045	Normal
DDCU Efficiency	Values in Figure 2	± 0.0075	± 0.0037	Normal

IV. Important Factors

Two new terms are introduced in this analysis. The two terms are 1) Risk Factors and 2) Power Risk Factors. The terms are used to attempt to meaningfully quantify the influence of the input random variables on the response variables. The underlying assumption, in both cases, is that the results from which these factors are determined behave like a Gaussian (normal) population. The definitions of these terms are as follows.

Risk Factors: These factors are developed for the independent variables that affect the power capability. The risk factor concept can be simply described using the uncertainty associated with each independent variable, and the sensitivity of the response (power output) with respect to each variable. In equation form:

$$\text{Risk Factor} = \text{Uncertainty} \times \text{Sensitivity.}$$

Although this equation does not include all the mathematics in the actual analytical approach used in the analysis described in this report, it is considered to be a useful representation of the risk factor concept applied here.

Power Risk Factors: The power risk factors are calculated directly from the SPACE output (without using FPI) for the variables perturbed one at a time. The total difference between the power output values corresponding to one positive (+ σ) and negative standard deviation (- σ) perturbation of each variable is divided into half to obtain the plotted values for one single standard deviation (σ). These factors are somewhat more useful to power analysis than the more typical Risk Factors, since they directly indicate the change in power output (in kilowatts (kW)) due to the uncertainty associated with a particular input variable.

V. Results and Analyses

Three different analyses were performed in order to examine three different probabilistic scenarios. Each of the cases assessed the current configuration of the ISS power system, which has 2 independent power channels – 2B and 4B. The solar arrays of the two power channels were set to operate in different modes, in an attempt to see if the results will vary based on this operating mode. The solar arrays on channel 2B were placed in a sun-tracking mode, while the channel 4B solar array was fixed in one location, so that the 4B solar array power varies throughout the orbit. SPACE was used to predict the maximum power capability on each power channel, based on the model inputs. FPI was then used to evaluate the effects of the uncertainties on the output power. Each of the three probabilistic analyses is described in detail in the following sections.

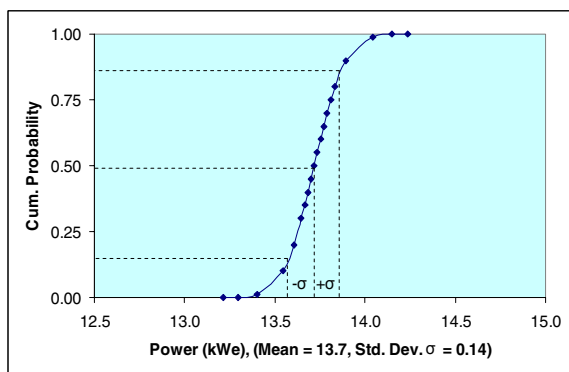
A. Three variables with baseline uncertainties

A preliminary analysis was performed varying only three of the input variables: Earth albedo, attitude error and battery capacity. The other two variables were considered to be constant, so they were not perturbed. This analysis uses the baseline standard deviations for the uncertainties, as listed in Table 1.

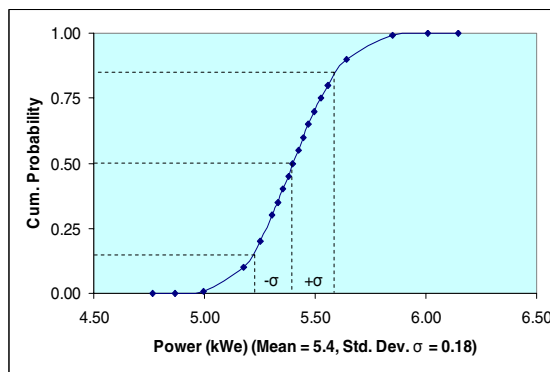
Based on the above described input, cumulative distribution functions (CDFs) for the two response variables, namely power outputs of Channels 2B and 4B, were calculated and are plotted in Figures 6 and 7, respectively. The mean value and standard deviation for Channel 2B output are 13.7 kW and 0.14 kW, respectively. For Channel 4B the mean value and standard deviation for the power output are 5.4 kW and 0.18 kW, respectively. Note that the channel with the sun-tracking solar arrays (2B) produces significantly more power than the channel with fixed

arrays. This is to be expected. More interesting is that the standard deviation is larger for the lower power channel than the higher power one.

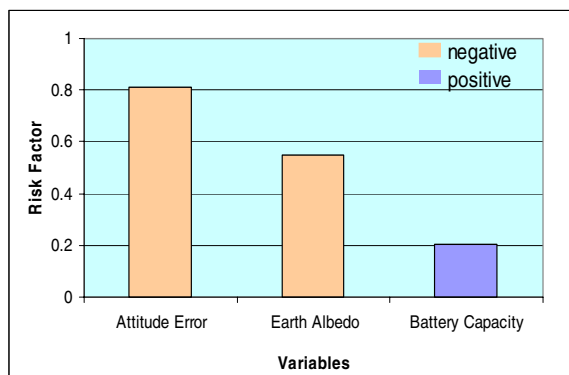
The risk factors for these three variables are then shown in Figures 8 and 9. The risk factors have been calculated using the formula shown before. Notice that the magnitudes of risk factors for the two channels are different. Attitude error is the most contributing factor in the higher power channel. Earth albedo is the most contributing factor for the lower power channel, with the attitude error being the least contributing factor. The risk factors for attitude error and Earth albedo in Figure 8 are negative, meaning that the current mean value of these variables have negative effects on the response value of the power output and that the mean value of these variables must be increased to increase the power output. Similarly in Figure 9, the Earth albedo factor is negative.



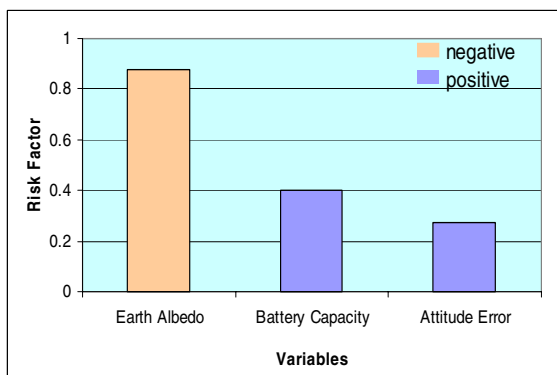
**Figure 6: Probability of Power Output
Channel 2B – 3 Variables**



**Figure 7: Probability of Power Output
Channel 4B – 3 Variables**



**Figure 8: Risk Factors for Variables (Channel 2B)
Tracking Solar Arrays / High Power Output**



**Figure 9: Risk Factors for Variables (Channel 4B)
Fixed Solar Arrays / Low Power Output**

B. All five variables with baseline uncertainties

In this analysis, the variation in power output is determined using all five random variables, Earth albedo (EA), attitude error (ATT), battery capacity (BA), DDCU efficiency and BCDU efficiency. The cumulative distribution functions for the two response variables, namely Channel 2B and 4B power output, were calculated using FPI and plotted in Figures 10 and 11. From these plots, the mean value for Channel 2B output power is 13.7 kW and the standard deviation is 0.22 kW, and for Channel 4B the mean value is 5.4 kW and standard deviation is 0.20 kW. The mean values are the same as for the 3 variable case (as they should be), but the standard deviation is slightly higher in the 5 variable case.

The risk factors for the two response variables are shown in Figures 12 and 13. BCDU efficiency, DDCU efficiency, and attitude error, unlike result of the three variable case, all have about the same magnitude for the higher power channel. For lower power channel, the Earth albedo has the highest risk factor, similar to the result for the 3 variable case. The risk factors for DDCU and BCDU efficiencies, attitude error and Earth albedo in Figure 12

are negative, implying that an increase in that value will increase power output. Similarly in Figure 13, the factors are negative for the Earth albedo, BCDU and DDCU efficiencies.

Power risk factors have been estimated for this analysis and are plotted in Figures 14 and 15 for Channel 2B and 4B, respectively. As mentioned before, these power risk factors represent the change in the power output corresponding to a change in the input variable by one standard deviation (σ), negative or positive.

Power risk factors in Figure 14 and 15 agree fairly well with risk factors obtained using FPI plotted in Figures 12 and 13 for each channel. There is a minor difference, being that the order of influence of the BCDU efficiency and the battery capacity are interchanged in the two analyses. However, the difference between the magnitudes of the two factors is negligible. The reason for this difference is because of the assumption of the nature of distribution for battery capacity. Risk Factors assume that battery capacity has a weibull distribution whereas power risk factors assume a normal distribution. When a normal distribution was used for battery capacity risk factors, the two results were identical.

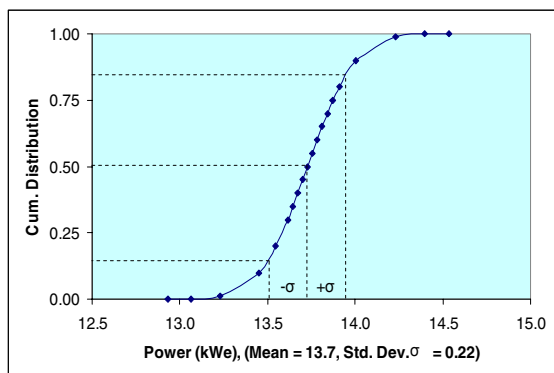


Figure 10: Probability of Power Output Channel 2B – 5 Variables

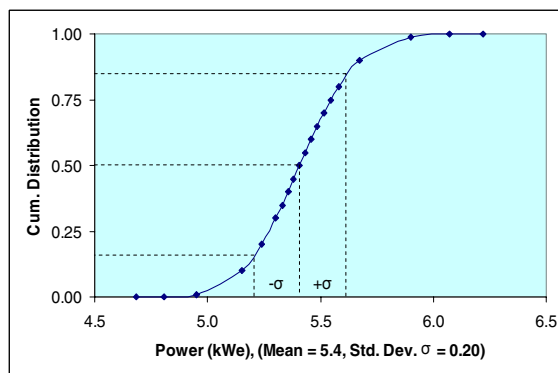


Figure 11: Probability of Power Output Channel 4B – 5 Variables

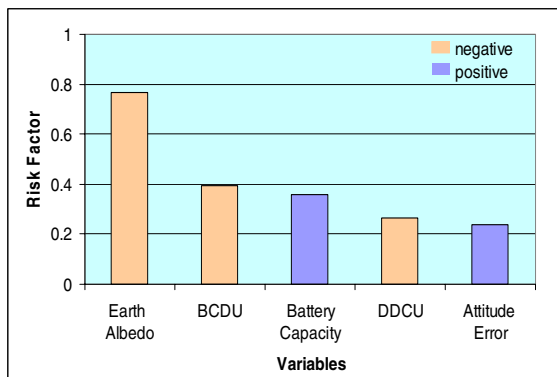


Figure 12: Risk Factors for Variables (Channel 2B) Tracking Solar Arrays / High Power Output

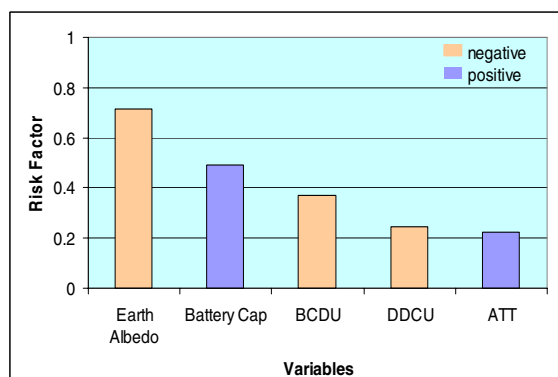


Figure 13: Risk Factors for Variables (Channel 4B) Fixed Solar Arrays / Low Power Output

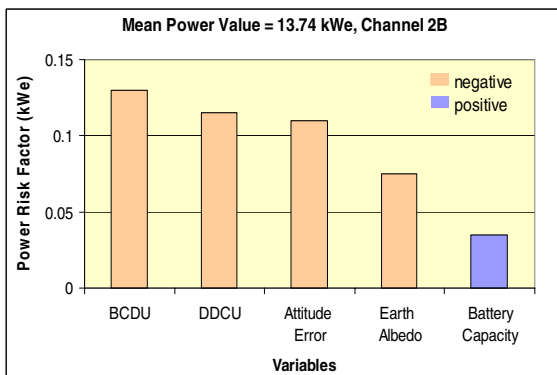


Figure 14: Power Risk Factors Channel 2B 5 Variables, Using 1 standard deviation

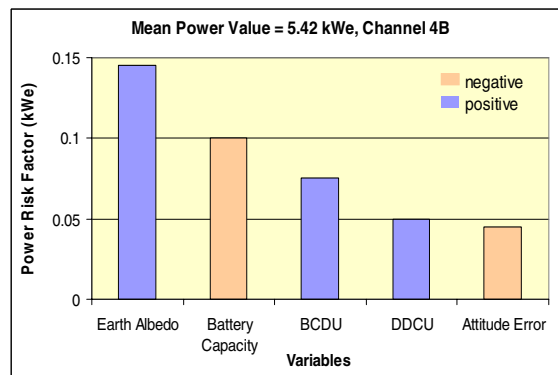


Figure 15: Power Risk Factors for Channel 4B 5 Variables, Using 1 standard deviation

C. All five variables using reduced uncertainties one variable perturbed at a time.

This analysis was performed to study the effect of reducing the uncertainties in the dominant random variables only. The dominant variables, the variables which have the highest influence on the response variables (i.e. those with tall sensitivity bars), have been identified as the BCDU efficiency, DDCU efficiency, and attitude error for Channel 2B. For Channel 4B, the Earth albedo, battery capacity, and BCDU efficiency are the dominant random variables. This reduction in uncertainty is done to determine what type of impact there would be on the uncertainty in power output, when reducing the uncertainty in the input variables. This result can be used to determine the relative value in expending effort to reduce the uncertainty in the input variables.

To study the effect of reducing uncertainties in these dominant random variables, the standard deviations of the uncertainties are reduced to half (an arbitrary choice) of the baseline values. Three different sets of combinations, named Cases 1-3, of reduced and baseline uncertainties were assessed. The three combinations, for both channels 2B and 4B, are described below. The reduced and baseline values of standard deviations are given in Table 1 and illustrated in Figure 16.

For each channel, Case 1 uses the baseline standard deviations for all variables. For Channel 2B, Case 2 reduces the standard deviations in BCDU efficiency only, and Case 3 reduces standard deviations for the uncertainties in Attitude Error, DDCU efficiency and BCDU efficiency. These cases are summarized in Table 2.

Similarly, the cases for Channel 4B, are summarized in Table 3. For Channel 4B, Case 5 reduces the standard deviation of the Earth albedo only, while Case 6 reduces the standard deviations of Earth albedo, battery capacity and BCDU efficiency.

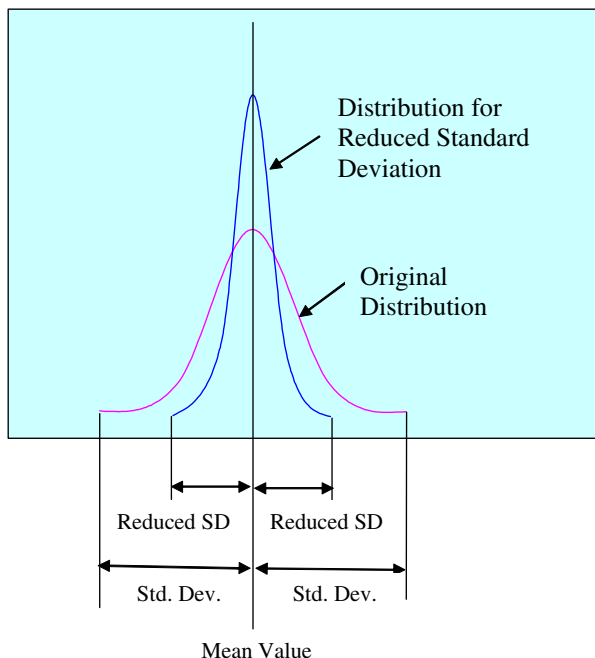


Figure 16: Normal Distribution of Random Variables Example for Cases 1-6

Table 2: Baseline and Reduced Standard Deviation in the Study of Channel 2B

Random Variable	Standard Deviation Case 1	Standard Deviation Case 2	Standard Deviation Case 3
Earth Albedo	± 0.09	± 0.09	± 0.09
Attitude Error	± 3.0	± 3.0	± 1.5
Battery Capacity	± 8.6227	± 8.6227	± 8.6227
BCDU Efficiency: Charge Discharge	± 0.009	± 0.0045	± 0.0045
	± 0.009	± 0.0045	± 0.0045
DDCU Efficiency	± 0.0075	± 0.0075	± 0.00375

Table 3: Baseline and Reduced Standard Deviation combinations for Channel 4B

Random Variable	Standard Deviation Case 4	Standard Deviation Case 5	Standard Deviation Case 6
Earth Albedo	± 0.09	± 0.045	± 0.045
Attitude Error	± 3.0	± 3.0	± 3.0
Battery Capacity	± 8.6227	± 8.6227	± 4.31135
BCDU Efficiency: Charge Discharge	± 0.009	± 0.009	± 0.0045
	± 0.009	± 0.009	± 0.0045
DDCU Efficiency	± 0.0075	± 0.0075	± 0.0075

Once again SPACE was used to obtain the power output for both channels. The cumulative distribution function, sensitivities and probability distributions for each channel were obtained using FPI. The cumulative distribution functions (CDF) and the probability Density Functions (PDF) for Channel 2B for all three cases are plotted in Figures 17 and 18, respectively. These figures clearly show that reducing the uncertainties in the dominant variables significantly reduce the uncertainty in the channel output.

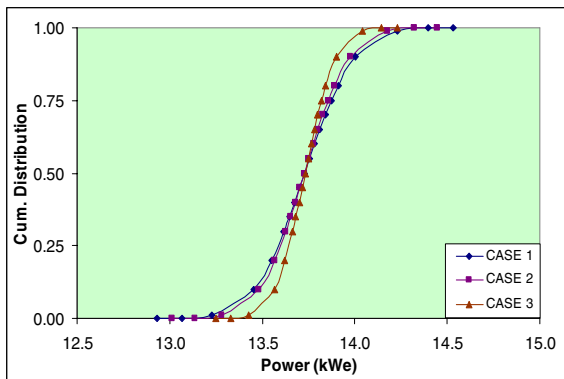


Figure 17: Cumulative Distribution Functions for Power Output for Channel 2B

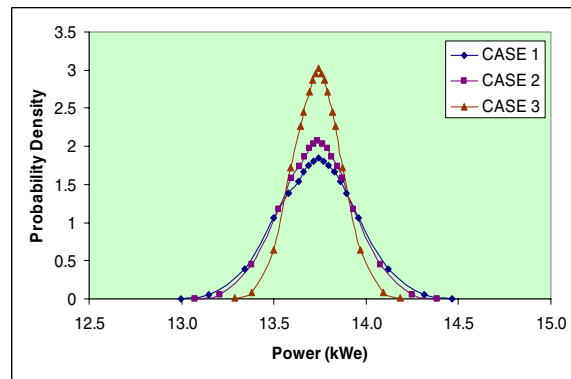


Figure 18: Probability Density Function for Power Output for Channel 2B

Similarly, for Channel 4B, the CDFs and PDFs for three cases are plotted in Figures 19 and 20, respectively.

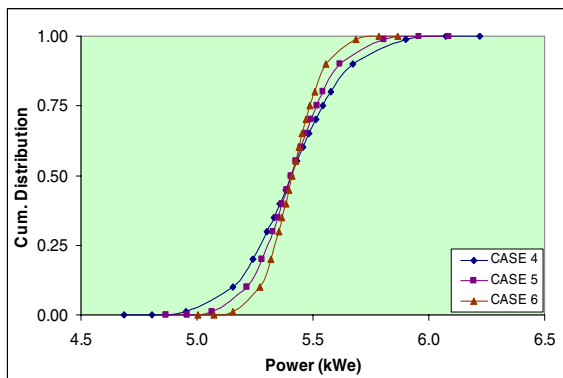


Figure 19: Cumulative Distribution Functions for Power Output for Channel 4B

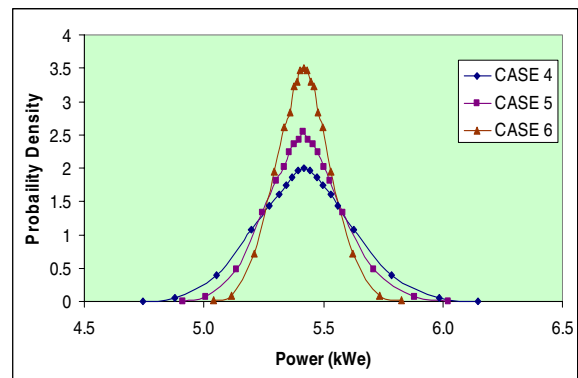


Figure 20: Probability Density Function for Power Output for Channel 4B

The power output ranges for the three cases for Channel 2B (the higher power channel) are included in Table 4. The uncertainty in the power output is reduced by 38% (Case 3) when the uncertainties in the dominant random variables are reduced by a factor of 2, where as only reducing the uncertainty in BCDU efficiency by a factor of 2 (Case 2) does not have a significant effect.

Table 4: Summary of Power Density Function results Channel 2B for Cases 1, 2 and 3

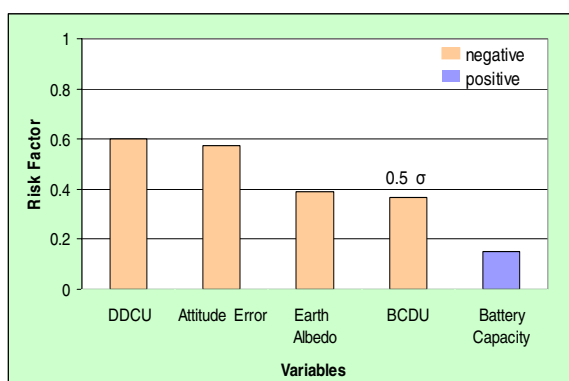
CASE	Power Output Values (kWe)	Power Output Range (kWe)	Percent Reduction
CASE 1: Baseline Std. Dev. Values	12.9 – 14.5	1.6	0
CASE 2: Reduced Std. Dev. for BCDU	13.0 – 14.4	1.4	13
CASE 3: Reduced Std. Dev. for Attitude Error, BCDU and DDCU	13.2 – 14.2	1.0	38

The power output ranges for the three cases for Channel 4B (the lower power channel) are included in Table 5. A 40% (5% more than Channel 2B) reduction in uncertainty of power output is achieved for Channel 4B by reducing the uncertainties of the dominant variables by a factor of 2. These reductions can be clearly seen in Figure 20. This would indicate that a larger gain in the confidence of power predictions can be achieved for the fixed solar array case than for the sun-tracking solar array case.

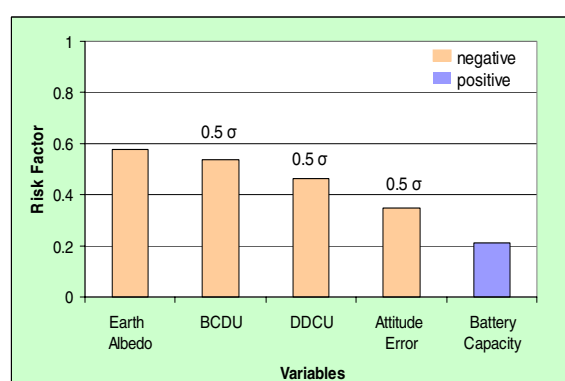
Table 5: Summary of Power Density Function results Channel 4B for Cases 4, 5 and 6

Case	Power Output Values (kWe)	Power Output Range (kWe)	Percent Reduction
CASE 4: Baseline Std. Dev.	4.7 – 6.2	1.5	0
CASE 5: Reduced Std. Dev for Earth Albedo	4.9 – 6.1	1.2	20
CASE 6: Reduced Std. Dev. for Earth Albedo, Battery Capacity and BCDU	5.0 – 5.9	0.9	40

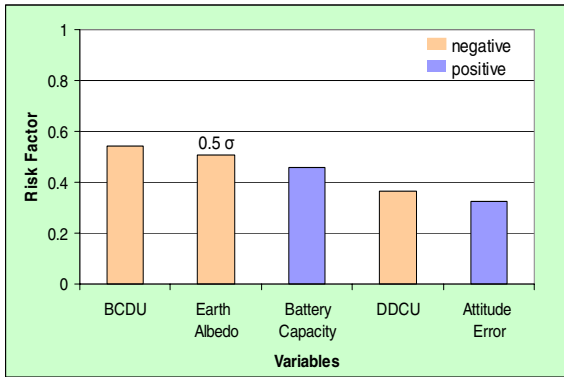
The results of risk factor analysis are plotted in Figures 21-24 for the reduced uncertainties. Figures 21 and 22 shows the effects of reducing the uncertainties on Channel 2B and can be compared to the risk factor plots shown in Figure 12. Figures 23 and 24 shows the risk factors for Channel 4B and can be compared to the risk factors shown in Figure 13.



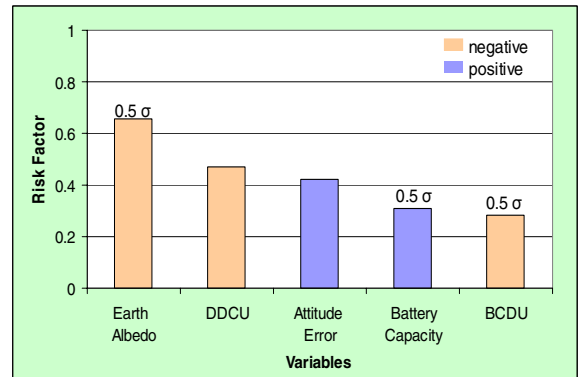
**Figure 21: Channel 2B Risk Factors – CASE 2
Reduced Standard Deviation for BCDU efficiency**



**Figure 22: Channel 2B Risk Factors – CASE 3
Reduced Standard Deviation for BCDU,
DDCU and Attitude Error**



**Figure 23: Channel 4B Risk Factors – CASE 5
Reduced Standard Deviation for Earth Albedo**



**Figure 24: Channel 4B Risk Factors – CASE 6
Reduced Standard Deviation Earth Albedo,
Battery Capacity and BCDU**

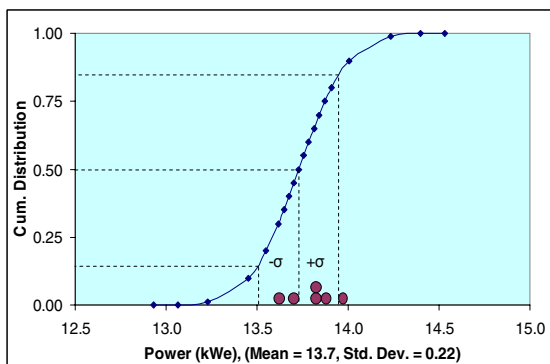
VI. Validation of Probability Distribution using multiple variable perturbation

An effort was made to attempt to verify that this simplified method, using FPI, produces a valid CDF for the power output. This is important, since using this method required only a few runs of SPACE to determine the distribution function, as opposed to the hundreds or thousands of runs that would be required in a traditional Monte Carlo technique. Since the cases run for use with FPI only varied one input variable at a time, it was decided to *spot check* the distribution by running a few cases where multiple input variables were perturbed simultaneously. If the distribution generated by FPI is valid, the results of these new runs should fall within or very near one standard deviation from the mean. If any of the results were to fall far outside of this band, that would call into question the validity of the FPI distribution.

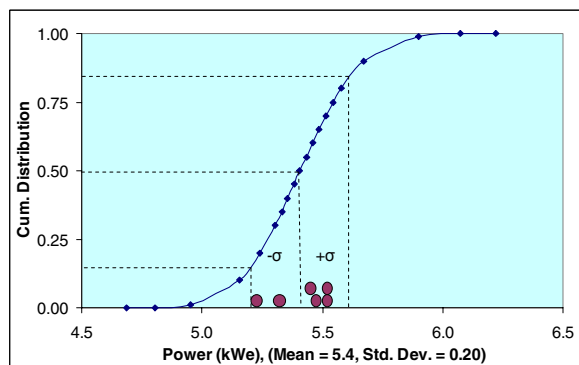
Six cases were selected to be run with SPACE to validate the FPI result. Each case perturbed either 2 or 3 of the independent variables simultaneously. These six cases are listed below. A plus sign (+) means that the variable was perturbed one standard deviation in the positive direction, while a negative sign (-) indicates the variable was perturbed in the negative direction.

- | | | |
|---------------------|-------------------|-------------------|
| 1. + Earth albedo | + Attitude error | |
| 2. + Earth albedo | + Attitude error | + DDCU efficiency |
| 3. - Earth albedo | + Attitude error | + DDCU efficiency |
| 4. - Earth albedo | - Attitude error | + DDCU efficiency |
| 5. - Attitude error | + DDCU efficiency | |
| 6. - Attitude error | + DDCU efficiency | + BCDU efficiency |

Figures 25 and 26 show the results of the SPACE runs for the six cases, above, plotted across the bottom of the CDF produced by FPI. The output power consistently falls well within the range of the CDF for each case, and for both Channels.



**Figure 25: Probability of Power Output
Channel 2B – Multiple variable perturbation**



**Figure 26: Probability of Power Output
Channel 4B – Multiple variable perturbation**

VII. Summary and Conclusions

A probabilistic approach was applied to the prediction of power capability of the International Space Station power system. The approach used the FPI code which requires significantly fewer analysis runs, compared to a more traditional Monte Carlo technique. The approach used estimated uncertainties in five random variables: 1) Earth albedo, 2) DDCU efficiency, 3) BCDU efficiency, 4) attitude error, and 5) battery capacity. The distributions of the power output from two channel ISS power channels were determined. These distributions quantified the mean values of the power outputs for each of two channels.

Also, the influence of all the random variables and uncertainties in them were quantified on the power output and the ones (dominant) which had significant influence were identified using sensitivity analysis. In a subsequent analysis, reductions in the uncertainties of the power output from the two channels were quantified when the uncertainties in the dominant variables were reduced.

Finally, the distributions generated by FPI were checked by running some test cases where multiple input variables were perturbed simultaneously. It was found that the results of all of these validation cases fell within the expected ranges in the CDF.

This work has successfully demonstrated that the probabilistic methods developed for aerospace structural analysis can be applied equally as well to spacecraft power system modeling. This capability can give spacecraft designers, mission planners and spacecraft operators new insight into the power margins that are available in their systems. In particular, since this initial study utilized the ISS power system as a case study, this new capability could be used to allow the ISS operators to operate the power system closer to its operating limits with higher confidence in its successful operation.

VIII. Future Work

The effort will continue to identify additional variables, quantify them in terms of random variation, and evaluate the influence of these uncertainties on available power from the International Space Station power system.

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13. ABSTRACT (Maximum 200 words) This paper describes the methods employed to apply probabilistic modeling techniques to the International Space Station (ISS) power system. These techniques were used to quantify the probabilistic variation in the power output, also called the response variable, due to variations (uncertainties) associated with knowledge of the influencing factors called the random variables. These uncertainties can be due to unknown environmental conditions, variation in the performance of electrical power system components or sensor tolerances. Uncertainties in these variables, cause corresponding variations in the power output, but the magnitude of that effect varies with the ISS operating conditions, e.g. whether or not the solar panels are actively tracking the sun. Therefore, it is important to quantify the influence of these uncertainties on the power output for optimizing the power available for experiments.				
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